VORPAL as a Tool for the Study of Laser Pulse Propagation in LWFA

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Abstract. The dimension-free, parallel, plasma simulation code VORPAL, has been used to study laser pulse propagation in Laser Wakefield Acceleration (LWFA). VORPAL is a hybrid code that allows multiple particle models including a cold-fluid model. The fluid model implements a simplified flux corrected transport in the density update but solves the momentum advection directly to allow for simulations of zero density. An implementation of Zalesky's algorithm for FCT is in development. VORPAL simulations predict the rate of loss of energy by pulses propagation through plasma due to Raman scattering. A PIC model for the plasma particles is in development.

1 Introduction

The concept of Laser Wake Field Acceleration (LWFA) has generated considerable excitement in the physics community with its promise of generating extremely high accelerating gradients [1–3]. The basic idea is that a high intensity, short pulse laser is fired into a plasma. The laser pushes the electrons in the plasma out of the pulse by the pondermotive force. A restoring force is produced from the remaining positive charges which pulls the electrons back into region, setting up a plasma oscillation behind the laser pulse. The result is a wake traveling at relativistic speeds behind the laser pulse.

There are of course many technical obstacles that must be overcome before an actual Laser Wake Field Accelerator can be built. There has been on going experimental and theoretical work to explore the details of LWFA. Our plasma simulation code VORPAL is a powerful computational tool for work in this area. We present the results of low noise simulations of wake field generation in both two and three dimensions. Studies of pulse energy loss due to Raman scattering are shown as well. We also discuss additional features in development for VORPAL and their applications to LWFA.

2 VORPAL

VORPAL - Vlasov, Object-oriented, Relativistic, Plasma Analysis code with Lasers - was begun as a prototype code to explore the possibility of using modern computing methods, in particular object-oriented design, to create a dimension free general plasma simulation code that would support multiple models.

Our code is dimension free, which means the dimension of the simulation is not hard coded but can be set at run time. This is done with the use of the templating feature of C++ and a method of coding we developed using recursion and template specialization. Three components are needed for dimension free coding. The first is a generalization of an iterator, which allows us to deal with the problem of indexing an array in an arbitrary dimension. The second is a class which holds a collection of iterators to perform a calculation on the grid. The last is a class which is responsible for updating the holder classes over a region of the grid.

A simple example of an iterator in one dimension is the bumping of an index for a one-dimensional array. One can bump the index either up or down. The index is then used to access the value stored at that location in the array. We generalize this by allowing our multi-dimensional iterator to be bumped in any direction. To implement a calculation on the grid, we use classes who contain collections of iterators and an update method that combines these iterators in a manner that produces the desired calculation. We refer to these classes as holders. They contain a iterator that points the result of the calculation, a set iterators that point to dependent fields, and an update method that implements the calculation.

A walker class, which is templated over dimension and direction, moves the holder class along the grid though recursion. The walker update method moves the iterator along the direction over which it was templated. While moving along that direction, the update method recursively calls the update method for the walker of the next lower direction. The walker for the lowest direction is specialized to perform the update of the holder class. Inlining these recursive calls provides the flexibility of setting the dimension at run time without loss to performance.

In addition to being dimension free, VORPAL is designed to run on most UNIX based platforms. It can be run on a single workstation as serial code or it can be run on parallel on both Linux Beowulf clusters and on high performance supercomputers. We have developed a general domain decomposition that allows static load balancing and gives the possibility of implementing dynamic load balancing with minimal re-engineering. This is done by using the idea of intersecting grid regions. Each domain has a physical region which it is responsible for updating and a extended region which is the physical region plus a layer of guard cells. To determine what needs to be passed from one processor to another, we just take the intersection of the receiving domain's extended region with the sending domain's physical region. This allows a decomposition into arbitrary box shaped regions.

Using the object oriented ideas of polymorphism and inheritance, VORPAL can incorporate multiple models for both the particles and fields in a plasma. At present we have cold fluid model implemented for the particles and a Yee mesh finite differencing for the fields. The fluid density update is done with a simplified flux corrected transport where the total flux leaving a cell in any direction is given an upper bound so it does allow the density in a cell to become negative. We are presently developing a full flux corrected transport for the density based on the algorithm developed by Zalesky. Rather than do a flux conservative update for the fluid momentum density as well, we directly advect the fluid momentum allowing us to simulate regions of zero density. A PIC model for the particles is also in development, which will allow us to run hybrid simulations for LWFA where the accelerated particles will be represented by PIC while the bulk plasma is modeled as a fluid to reduce noise.

3 Applications to LWFA

VORPAL was used to simulate the generation of a wake field by a laser pulse being launched into a ramped plasma in both two and three dimensions. In 2D the plasma is 40 μm in the direction of propagation and 100 μm in the transverse direction. Figure 1 shows the initial plasma density along along the direction of pulse propagation. The density is zero for the first 10 μm of the simulation, rises over 10 μm to 3.e25 m^{-3}, and is constant for the remaining 20 μm. There are 480 grid points in the direction of propagation and 100 grid in the direction transverse to propagation and the time step is 15 fs. An electromagnetic wave is injected from the boundary and propagates towards the ramp. The pulse is Gaussian in the transverse direction and is a half sine in the direction of propagation. The peak power of the laser pulse is 1.07 TW and the its total energy is 61.9 mJ. After 31 μm of propagation, a moving window is activated, so that the plasma appears to move to the left, while the laser pulse appears stationary. During injection, the laser causes peaking of the plasma by a factor of three or so, but no negative densities or numerical instabilities are observed.

In this simulation the pulse width was set to be half the wavelength of the plasma oscillations so a strong wake field is produced. In Fig. 2 we see a contour plot of the electric field parallel to the direction of propagation after the pulse has propagated 187 ps. The bowing of the wake field is due to nonlinear effects and has been seen in PIC simulations done with XOOPIC [4] and in other fluid simulations done with Brad Shadwick's fluid code [5]. In Fig. 3 we see a line plot of the electric field in the parallel direction of slice running down the middle of the simulation region. Since a fluid model is used for the plasma, the results are almost noiseless.

Due to the flexibility of VORPAL's dimension free coding, only minor changes are needed to the input file of the 2D run to generate a 3D wake field simulation. Using the same parameters as the 2D run with the two transverse directions having the same dimensions, we repeat the our wake field generation simulation in 3D. In Fig. 4 we see a contour plot of the plasma density along the plane transverse to the direction of propagation located at the edge of the plasma. In other words, we are seeing the plasma density along a slice that is half way between the point where the initial density starts to rise from zero and the point where it levels off. The concave region that appears in the density plot is where

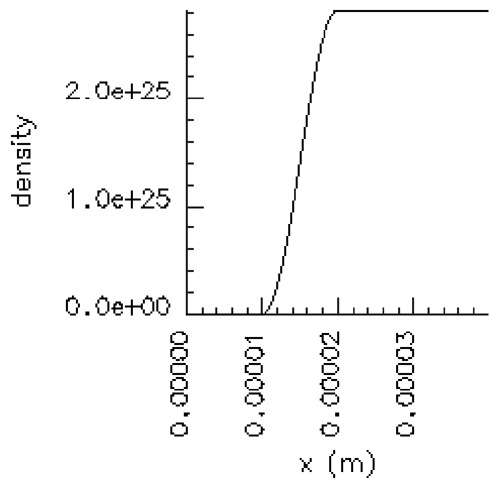

Fig. 1. The initial density of the plasma along the direction of propagation

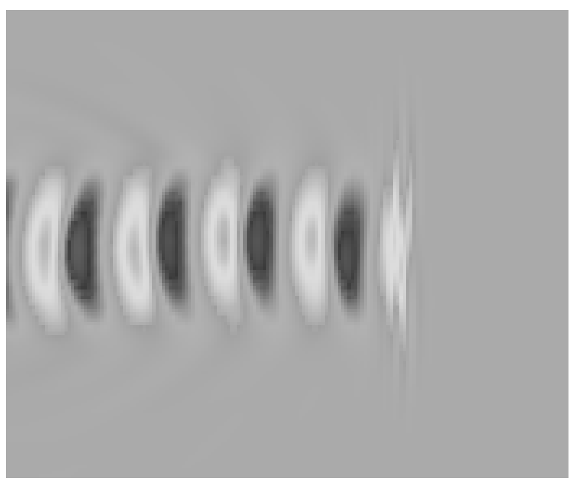

Fig. 2. The electric field in the direction of propagation after the laser pulse has propagated for 187.5 ps

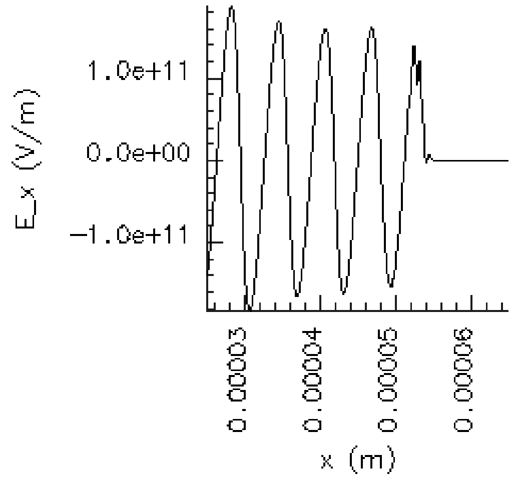

Fig. 3. The electric field in the direction of propagation after the laser pulse has propagated for 187.5 *ps*

the pondermotive force from the laser has pushed back the plasma, showing the region in the plasma where the electrons have been ejected. The electrons are pulled back into this region by the net positive charge from the plasma ions, which then sets up the plasma oscillations of the wake field.

Stimulated Raman scattering is an important effect for LWFA due to the energy loss it can induce. Raman scattering occurs when large amplitude light wave is scattered by the plasma into a light wave and a electron plasma wave. Raman scattering is triggered by small fluctuations in the plasma density such as those produced by noise. The electron plasma wave can then resonant with the scattered electromagnetic wave, generating an instability. Energy is transfered from the light wave to the electron plasma wave heating the plasma.

We simulated the propagation of a laser pulse in a plasma where pulse length is 2.5 times longer than the plasma wavelength. Again the plasma is ramped at one end of the simulation, rising to a peak density of 2.5e25 m^3 over 20 μm starting 20 μm from the edge of the plasma. The simulation region is 150 μm in the direction of propagation and 100 μm in the transverse direction with 2000 grid points in the propagation direction and 200 grid points in the transverse direction. The time step is 20 fs and the simulation is run for 9000 time steps. A laser pulse is injected from the boundary and propagates towards the plasma ramp. The pulse is Gaussian in the transverse direction and is a half sine in the direction of propagation. The peak power of the laser pulse is 1.21 TW and the its total energy is 70 mJ. After 127 μm a moving window is activated. In Fig. 5 we see the electric field in the direction of propagation after 4500 time steps. Behind the laser we see the electric field of the scattered electron plasma wave. Because we are using conducting boundary conditions, we see some reflections of the scattered wave from the boundaries. This does not affect the instability since

Fig. 4. The plasma density along a plane perpendicular to the direction of propagation shortly after the laser pulse has entered the plasma

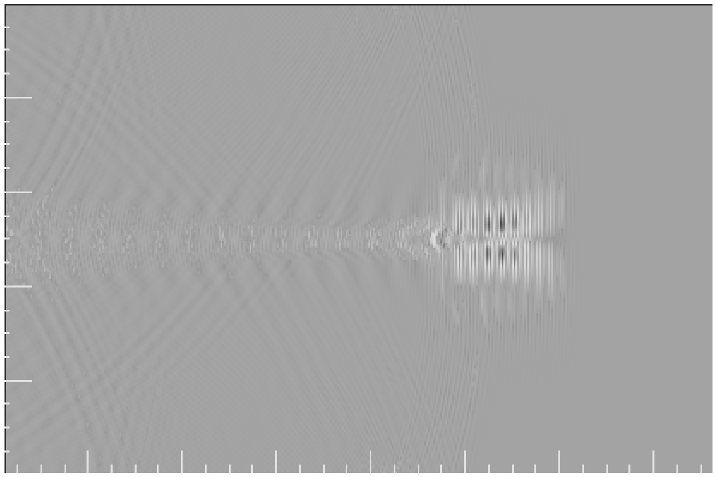

Fig. 5. The the electric field in the direction of propagation after 4500 time steps

the reflections occur well after the pulse. In Fig. 6 a line plot of the electric field along a plane running through the middle of the simulation shows the scattered wave a little clearer.

A method for controlling stimulated Raman scattering involving the use of chirped non-bandwidth limited laser pulse have been proposed [6] and recent experiments have been successful in reducing Raman scattering with this method. VORPAL's wave launching boundary has been modified to so chirped pulses can be simulated and we planning to apply our code to on going work in this area. Simulations of electron production in recent experimental work [7, 8] in chirped pulse propagation in plasma are planned once we have a PIC model for the plasma particles.

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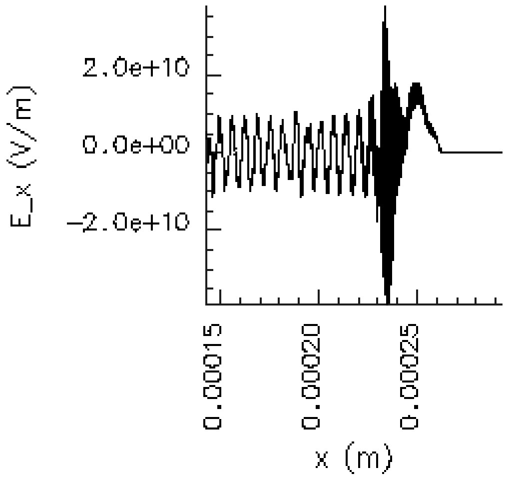

Fig. 6. The the electric field in the direction of propagation along a plane running through the middle of the simulation after 4500 time steps

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